A PALEOECOLOGICAL STUDY OF MARATHON COUNTY LAKES

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Introduction

Questions often arise concerning how a lake's water quality has changed through time as a result of watershed disturbances. In most cases there is little or no reliable long-term data. Questions often asked are if the condition of the lake has changed, when did this occur, what were the causes, and what were the historical condition of the lake? Paleoecology offers a way to address these issues. The paleoecological approach depends upon the fact that lakes act as partial sediment traps for particles that are created within the lake or delivered from the watershed. The sediments of the lake entomb a selection of fossil remains that are more or less resistant to bacterial decay or chemical dissolution. These remains include diatom frustules, cell walls of certain algal species, and subfossils from aquatic plants. The chemical composition of the sediments may indicate the composition of particles entering the lake as well as the past chemical environment of the lake itself. Using the fossil remains found in the sediment, one can reconstruct changes in the lake ecosystem over any period of time since the establishment of the lake.

A relatively inexpensive means of comparing present day conditions with pre-settlement conditions is top/bottom sediment cores. While a full core, which is assumed to cover a time period of European settlement, is collected, only the top and bottom sections are analyzed. It is assumed that the top section was deposited during the last 2-3 years. The bottom section is assumed to have been deposited prior to the arrival of Europeans during the latter part of the nineteenth century.

This report will examine six lakes of Marathon County (Table 1, Figure 1) that have potentially been impacted by anthropogenic activities. The most common potential change in the lakes is eutrophication through the introduction of excess nutrients to the lakes.

A single sediment core was collected from the deep area of the lake using a piston corer during November 2012. This corer has an inside diameter of 8.8 cm. The total length of the cores was between 90 and 100 cm. The cores were sectioned into 1 cm intervals for the top 40 cm and then at 2 cm to the bottom of the core. For this study usually the top section and a section very near the bottom of the core were examined for the diatom community composition. It is expected that the bottom sample was deposited at least 150 years ago and represent pre-settlement conditions in the lake.

Diatoms are a type of algae which possess siliceous cell walls and are usually abundant, diverse, and well preserved in sediments. They are especially useful for reconstructing past lake conditions as they are ecologically diverse and their ecological optima and tolerances can be quantified. Samples for diatom analysis were cleaned with hydrogen peroxide and potassium dichromate (van der Werff 1956). Cover slips on which a portion of the diatom suspension was dried were mounted on microscope slides with Naphrax®. Specimens were identified and counted under oil immersion objective (1000X) until at least 500 valves had been encountered. Diatoms were identified to species level whenever possible using references which included Patrick and Reimer (1966, 1975), Krammer and Lange-Bertalot (1986, 1988,

1991a,b), Camburn and Charles (2000), Krammer (2000), Lange-Bertalot (2001), and Siver et al. (2005) as well as primary species literature.

Results and Discussion

Aquatic organisms are good indicators of water chemistry because they are in direct contact with the water and are strongly affected by the chemical composition of their surroundings. Most indicator groups grow rapidly and are short lived so the community composition responds rapidly to changing environmental conditions. One of the most useful

Table 1. Lake Morphometry, hydrologic type and sampling location of the study lakes.

	Hydrologic Type	Location	Area (ha)	Maximum Depth (m)
Big Bass	Seepage	44.72350° 89.43348°	70	4.0
Mayflower	Seepage	44.91021° 89.24722°	40	4.9
Mission	Seepage	44.77910° 89.35352°	43	7.9
Norrie	Seepage	44.88565° 89.26161°	40	5.8
Pike	Drainage	44.81603° 89.34541°	83	10.4
Wadley	Seepage	44.69220° 89.42577°	19	8.2

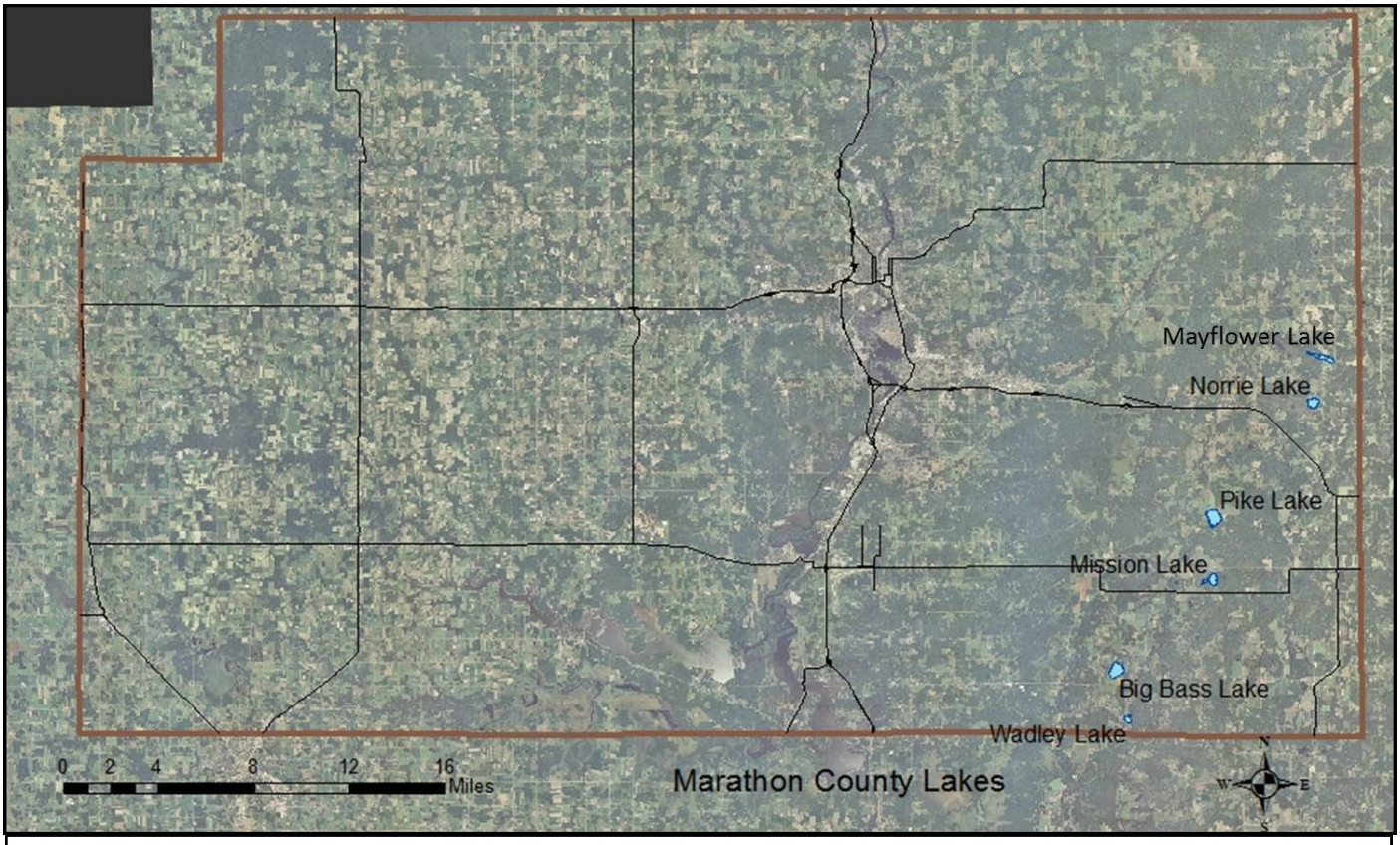

Figure 1. Map of Waushara County showing the study lakes. Deer Lake is not shown on this map as it was sampled as part of another study.

organisms for paleolimnological analysis are diatoms. They are a type of alga which possess siliceous cell walls and are usually abundant, diverse, and well preserved in sediments. They are especially useful as they are ecologically diverse and their ecological optima and tolerances can be quantified. Certain taxa are usually found under nutrient poor conditions while others are more common under elevated nutrient levels. They also live under a variety of habitats, which enables us to reconstruct changes in nutrient levels in the open water as well as changes in benthic environments such as aquatic plant communities. Figure 2 shows photographs of diatom species that were common in the sediment cores.

All of the lakes except Pike Lake are seepage lakes, meaning they have no surface inlets or outlets. Pike lake is a drainage lake which means it does have a surface inlet and outlet. Seepage lakes often have lower nutrient concentrations. Water chemistry samples collected and analyzed during the last few years found that these lakes would be classified as meso-eutrophic based upon their summer phosphorus levels (Table 2). Wadley Lake is the exception and its phosphorus and chlorophyll concentrations would place it in the mesotrophic range. These lakes, with the exception of Norrie Lake, have moderate alkalinity values and pH levels are from 7.5 - 8.0. Only Big Bass Lake had high chloride levels, probably the result of the application of salt for ice and snow removal on roadways. With the exception of Big Bass and Wadley lakes, these lakes are stained with high color values.

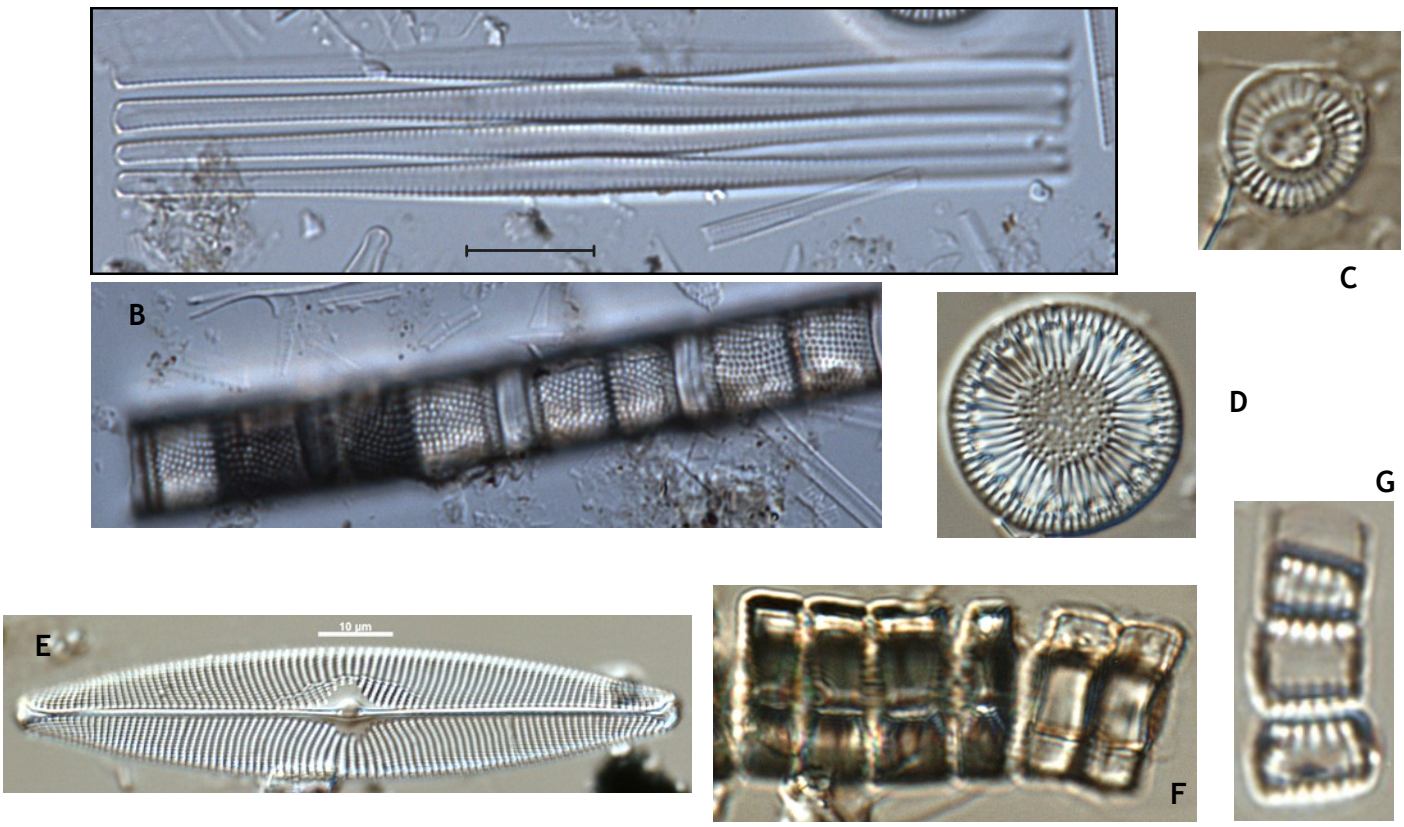

Figure 2. Photomicrographs of the common diatoms found in the sediment cores. The first four diatoms (A) *Fragilaria crotonensis,* (B) *Aulacoseira ambigua,* (C) *Discotella stelligera, and (D) Cyclotella bodanica* var. *lemanica* typically are found in open water environments. *Staurosira construens* ((F) and *Staurosira construens* var. *venter (G)* is commonly found attached to substrates such as aquatic plants, other filamentous algae or grow on the sediments and are often associated with higher nutrient concentrations. *Navicula vulpina* (E) grows on aquatic plants and is usually found in low nutrient environments.

Table 2. Summary of selected water chemical variables from the study lakes. Samples were collected and analyzed by the UW-Stevens Point during the period 2010-12. Secchi disk transparency, phosphorus and chlorophyll are mean values for the summer period while the other variables were sampled less frequently.

	Secchi (m)	Alkalinity ($mg\ L^{-1}$)	Color (PTU)	pH	Total P (µg L-1)	Total N ($\mu g\ L^{-1}$)	Chlorophyll a ($\mu g\ L^{-1}$)	Chloride ($mg\ L^{-1}$)
Big Bass	1.9	111	11	8.1	27	1590	4.8	10.1
Mayflower	2.1	122	48	7.8	23	1298	5.9	3.6
Mission	2.3	67	52	7.5	21	1143	8.4	2.9
Norrie	1.1	6	93	5.7	30	642	7.4	0.4
Pike	1.5	136	56	8.0	28	1482	15.0	8.7
Wadley	4.8	114	11	8.2	13	888	2.4	2.8

Big Bass Lake

There where almost no planktonic species in either the top or bottom sample in the core. This reflects the fact that this is a relatively shallow lake and the diatom community is associated with submerged aquatic plants and filamentous algae. The bottom sample is dominated by benthic taxa that indicate low nutrient levels, e.g. *Navicula vulpina* (Figure 1E) and *N. aurora*, *(Lange-Bertalot 2001)* (Figure 3). Other common taxa in the bottom sample that indicate low nutrients were *Eunotia soleirolii* and *Gomphonema* spp. The diatoms indicate that submerged aquatic plants were common but they were not very dense and phosphorus concentrations in the water were low. In the top sample there were lesser amounts of these taxa but instead most of the community was composed of benthic *Fragilaria*. This indicates that nutrient levels have increased to the point where filamentous soft bodied algae are present and the diatoms grow attached to these algae. Species richness is similar in the top and bottom samples and diversity is higher at the top (Table 3).

Table 3. Taxa richness and diversity for the study

Lake		Richness	Diversity
Big Bass	Top	69	3.27
	Bottom	66	2.65
Mayflower	Top	56	2.31
	Bottom	12	1.01
Mission	Top	83	3.17
	Bottom	46	2.18
Norrie	Top	82	3.06
	Bottom	68	3.24
Pike	Top	67	3.19
	Bottom	70	3.30
Wadley	Top	42	2.30
	Bottom	60	3.13

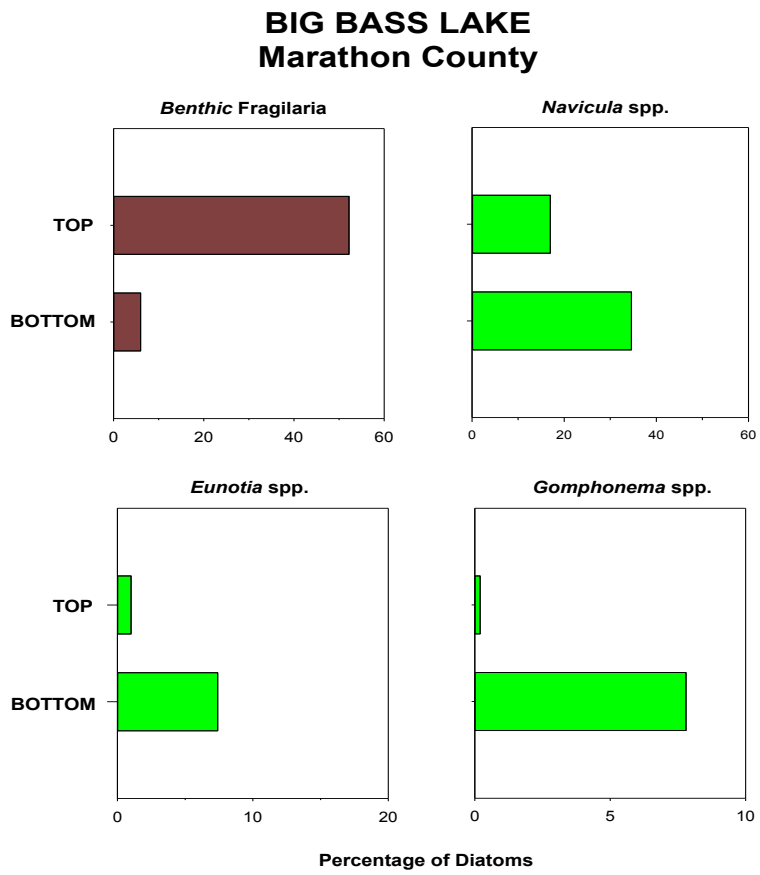

Figure 3. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Big Bass Lake.

Mayflower Lake

The majority of the diatoms in the top and bottom samples were benthic species (Figure 4). The dominant taxa in the bottom sample was *Staurosirella pinnata* but it was less common in the top sample. This alga is known to grow on sediments in addition to being associated with filamentous algae. In the top sample, planktonic diatoms were more common, although most diatoms still were of the benthic variety. The increase in planktonic diatoms suggests a decline in water clarity and is probably the reason for few *S. pinnata* in the top sample. In the top sample taxa richness and diversity is much greater compared with the bottom sample (Table 3) which supports the suggestion of more macrophytes at the present time. With the increase in abundance of macrophytes there are more niches for the diatoms to grow. This increase in diversity with increased nutrients is known as the intermediate disturbance hypothesis. This hypothesis suggests that moderate disturbances result in a more diverse community because increased productivity results in more habitats. If the disturbance becomes great enough then richness and diversity decline. The increased richness and diversity is very common in lakes in northern WI that have moderate shoreland development but the watersheds are otherwise forested. This shift suggests that at the present time there are more macrophytes then prior to settlement. This shift also suggests there has been an increase in phosphorus concentrations in recent decades. The increase in phosphorus levels is probably not large or there would a greater shift in planktonic species to eutrophic taxa.

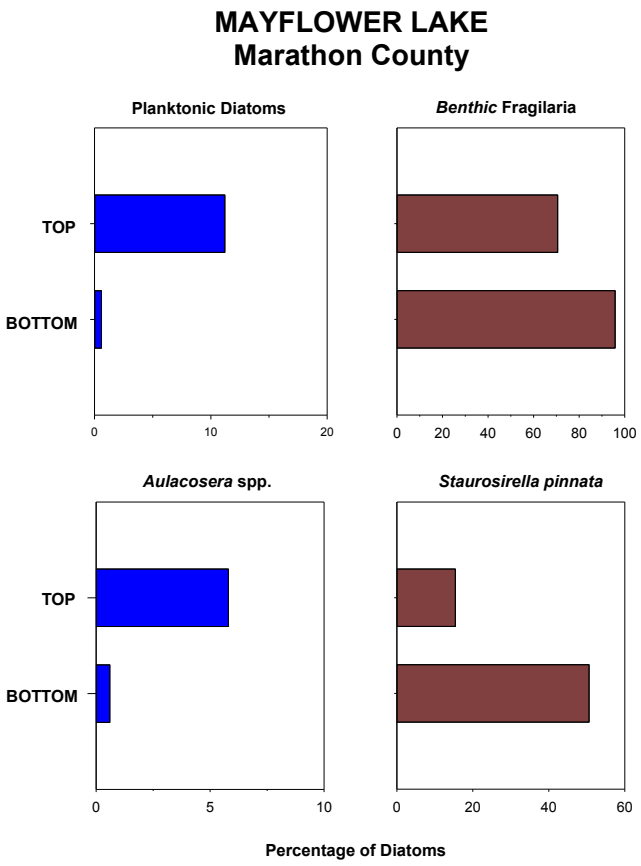

Figure 4. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Mayflower Lake.

Mission Lake

At the bottom of the core, benthic diatoms comprised over 75% of the diatom community (Figure 5). The dominant taxa were *S. pinnata* and *Staurosira construens*. These taxa are associated with sediments and submerged aquatic plants as well as soft bodied filamentous algae. At the top of the core the diatom community changed and the dominant type of diatoms were planktonic taxa. These types of diatoms float in the open water. In many lakes this change signals an increase in nutrients. As nutrient levels increase, water clarity declines and less light reaches the lake bottom thus inhibiting growth of benthic diatoms. Another change that would enhance the growth of planktonic diatoms is an increase in water color. At the present time the lake is very stained and if this has increased, it would also reduce the amount of light reaching the lake bottom.

Even though there has been a large increase in planktonic diatoms there are still a large number of benthic taxa. In fact the taxa richness and diversity are much higher in the top sample. This suggests that there are more submerged aquatic plants at the present time compared with pre-settlement times. A working hypothesis about the change in the lake's ecosystem during the last 100+ years is that prior to settlement, there were fewer macrophytes and water clarity was better. The better water clarity may have been the result of lower phosphorus concentrations or lower water color values.

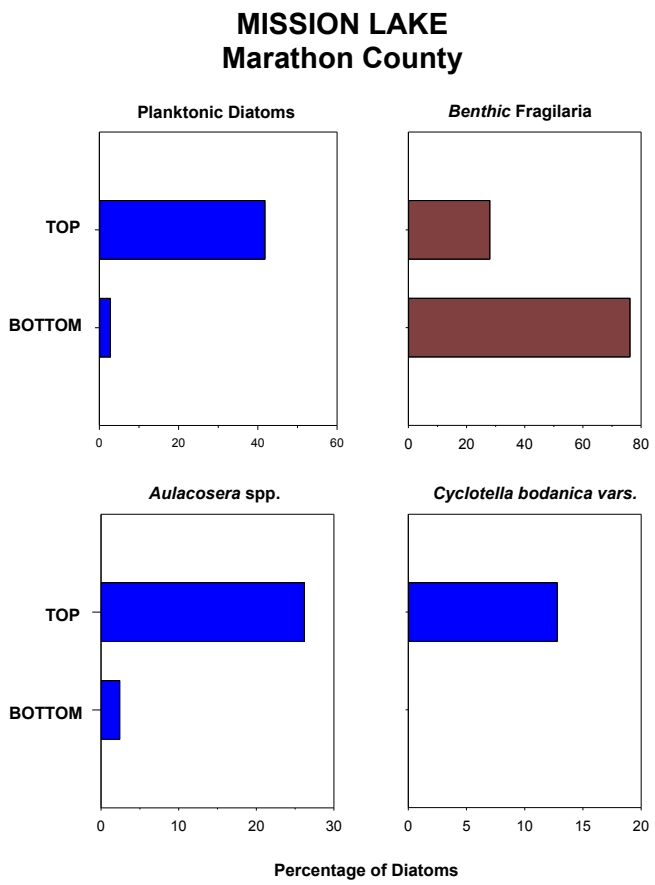

Figure 5. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Mission Lake.

Norrie Lake

This lake is much different than the other lakes in the study. While it has high color values, its pH is much lower (Table 2). It is likely that this lake receives little or no groundwater since it has such a low pH. Earlier studies have demonstrated that groundwater inflow is important in regulating the acid/base chemistry of softwater seepage lakes (Anderson and Bowser 1986, Eilers et al. 1983), because the alkalinity concentration of groundwater is much higher than that of precipitation. In Michigan's Nevins Lake, a drought-induced reduction in the input of solute-rich groundwater resulted in a substantial decrease in cation concentration, leading to lower alkalinity and pH values (Webster et al. 1990, Krabbenhoft and Webster 1995).

Garrison et al. (2008) found that alkalinity and pH are important determinants in the type of diatoms. The dominant diatoms in this lake are those associated with low pH values. The community is influenced as much by pH than phosphorus concentrations. At the bottom of the core, benthic diatoms made up over 80% of the community (Figure 6). The most common taxa was *Aulacoseira perglabra* var. *floriniae* which is typically found in acidic, oligotrophic lakes (Camburn and Charles 2000 and Siver et al. 2005). At the top of the core planktonic diatoms were much more common. One of the dominant taxa was *Asterionella ralfsii* var. *americana*. This diatom typically is found in low pH waters that are humic stained and high nutrient concentrations (Camburn and Charles 2000 and Siver et al. 2005). It appears that at the present time Norrie Lake is more highly colored with higher phosphorus concentrations as existed

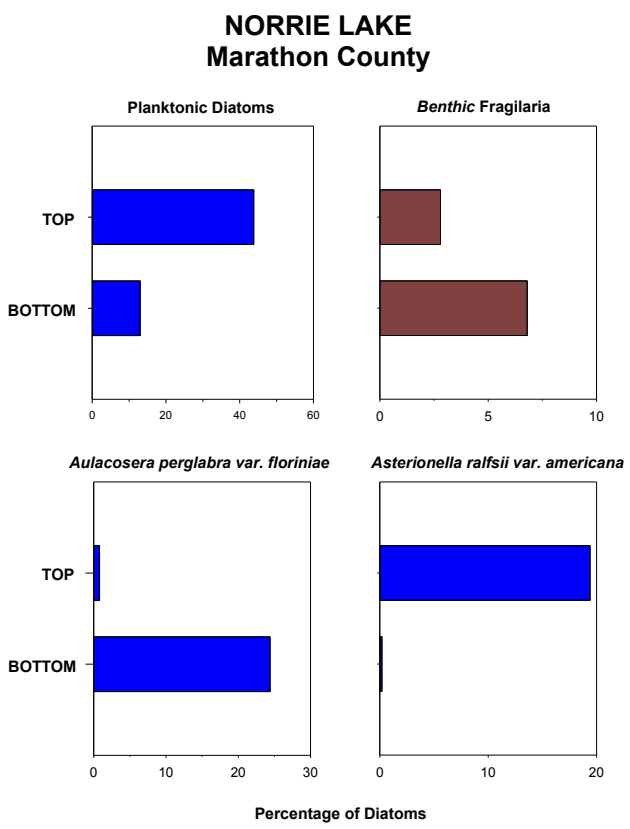

Figure 6. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Norrie Lake.

prior to settlement in the late 1800s.

Pike Lake

There were no diatoms preserved in the bottom sample from the core. It is not clear way this occurred but sometimes this happens when water levels are very low. Since the bottom sample appeared to contain a significant amount of peat, it may be that this lake was more like a wetland long time ago. A middle depth (34-35 cm) of the core was examined and it is assumed that this represents pre-settlement conditions. In the middle sample, benthic diatoms comprised about 60% of the diatom community (Figure 7). The dominant taxa were *S. pinnata* and *S. construens*, similar to the bottom sample in Mayflower Lake. In the top sample there was an increase in planktonic diatoms to 50%. In both the middle and top samples the dominant planktonic diatoms were *A. ambigua* and *A. granulata*. While *A. ambigua* is found at moderate phosphorus levels, *A. granulata* usually indicates higher nutrient concentrations. It is likely that phosphorus concentrations historically were moderately high and may not have changed much in the last 100 years. The historically higher phosphorus levels may reflect that Pike Lake is the only drainage lake in this study. Since drainage lakes have larger watersheds they naturally often have higher nutrient concentrations.

Wadley Lake

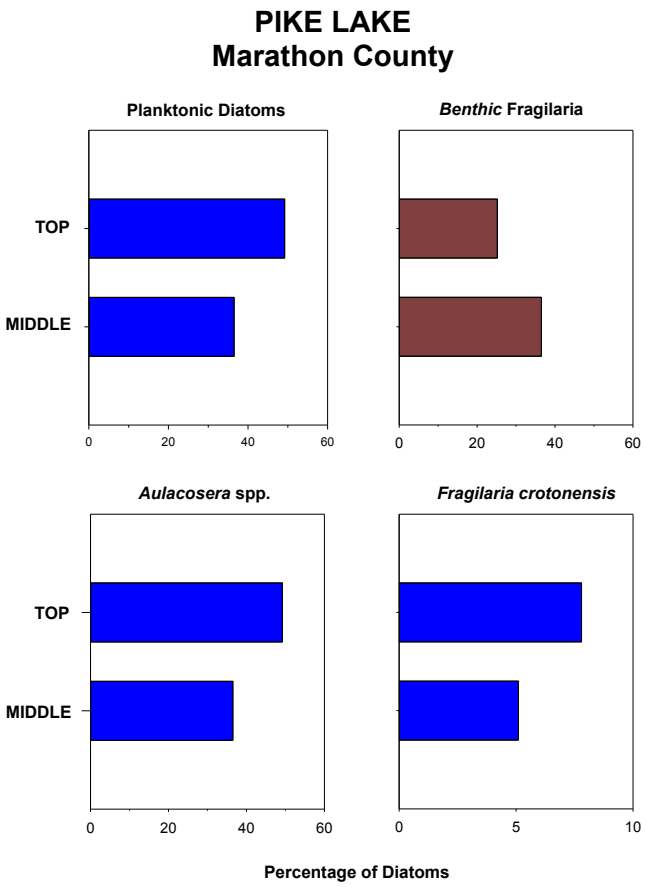

Figure 7. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Pike Lake.

The diatom communities in both the bottom and top samples in this lake are nearly all benthic taxa (Figure 8). Even though this lake has a relatively deep maximum depth, most of the lake is shallow. The bottom sample is dominated by taxa that grow attached to submerged aquatic plants and often are found in low to moderate nutrient concentrations. In the top sample most of the diatoms were in the group benthic *Fragilaria*. These taxa are often associated with filamentous soft bodied algae. The shift in the diatom community suggests that there has been an increase in phosphorus concentrations.

Data Analysis

In order to better understand how much the lakes have changed from historical times, a multivariate statistical analysis, detrended correspondence analysis (DCA), was performed on the diatom communities in the top and bottom samples of the study lakes (CANOCO 4.5 software, ter Braak and Smilauer 2002). The greater the separation between the bottom and top samples, the more the lake is different at the present time compared with its historical ecosystem. With this analysis it is not possible to know for sure what environmental conditions are most influencing the shift in the placement of the samples on the graph but we can hypothesize what the main factors are. It appears that the horizontal axis indicates a shift in the amount of submerged aquatic plants and filamentous algae and the vertical axis reflects changes in phosphorus and possibly water color. A shift from right to left, e.g. Wadley indicates an increase is plants and attached algae while a shift from the bottom to the top, e.g. Norrie indicates an increase in phosphorus

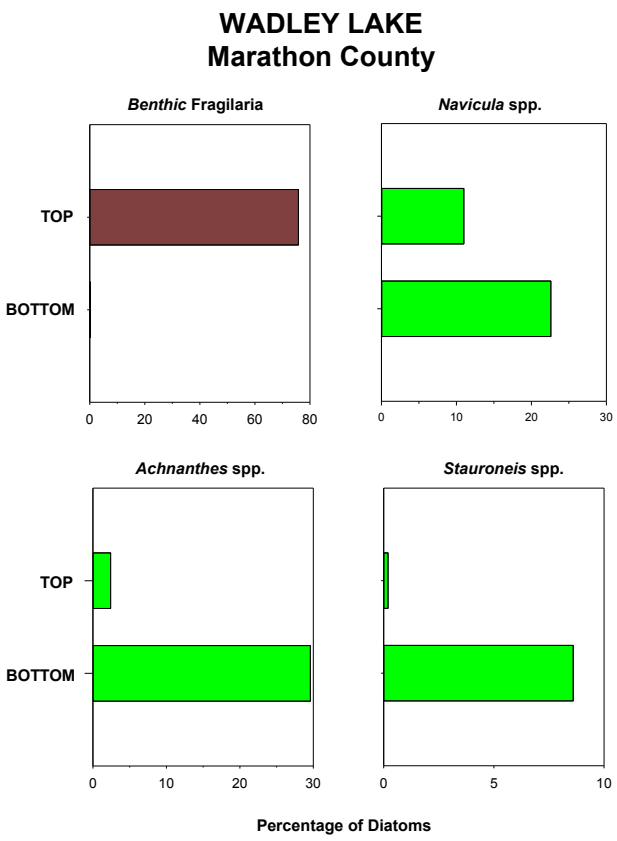

Figure 8. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Wadley Lake.

and water color. A multivariate analysis of 71 Wisconsin shallow lakes found that phosphorus and water color similarly affect the diatom communities (Garrison et al. 2008).

The lakes that showed the greatest change were Norrie and Wadley lakes (Figure 9). Norrie Lake is separated from the other lakes because of its low pH. Because of this it has a unique diatom community. Mayflower Lake shows the least change. The diatom community suggests that the change in Norrie Lake is caused by increased levels of phosphorus. Changes in Pike and Mission lakes are more ambiguous and may reflect changes in phosphorus or water color.

Weighted averaging calibration and reconstruction (Birks et al., 1990) were used to infer historical water column total phosphorus (TP) in the sediment core. A training set was developed from 53 Wisconsin lakes. The 53 lakes training set is based on lakes with total phosphorus values from 3 to 30 µg L^{-1}. Training set species and environmental data were analyzed using weighted average regression software (C2; Juggins 2003) to calculate TP optima for 128 taxa in the training set. The resulting transfer functions (bootstrapped 999 cycles $r^2 = 0.69$, $P < 0.05$) were subsequently applied with weighted averaging calibration to the fossil diatom assemblages (Birks et al., 1990, Juggins, 2003). Initial TP estimates from weighted averaging regression were corrected using inverse deshrinking. Bootstrapped error estimates are based on initial log transformed data with the TP log error being 0.164.

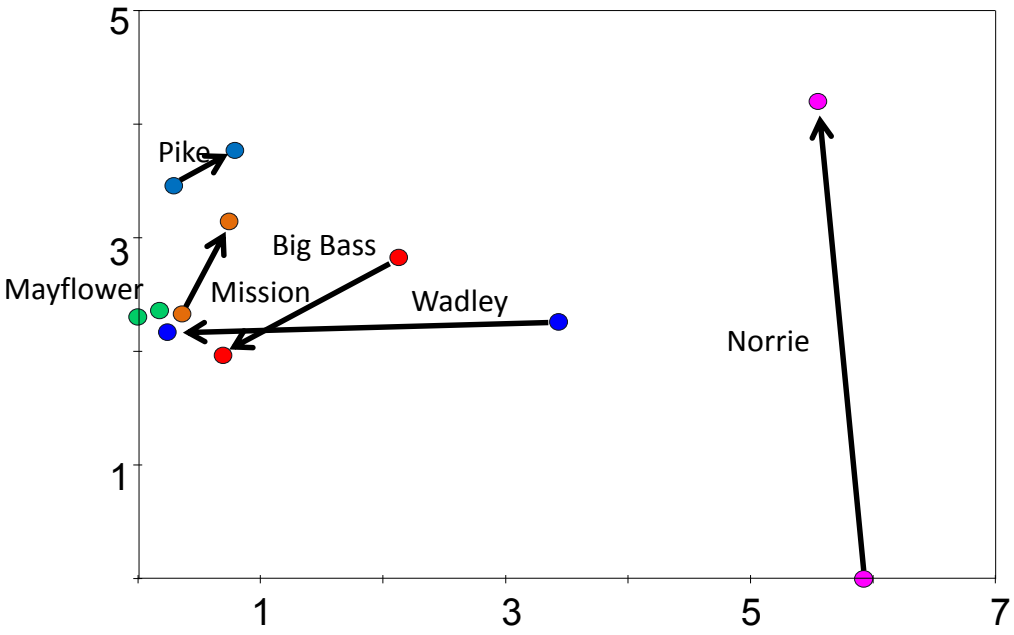

Figure 9. Discriminant correspondence analysis (DCA) for the diatom communities in the study lakes. The further apart the samples are the more dissimilar they are. Norrie and Wadley lakes are the most different between the top and bottom samples while Mayflower Lake shows little change over time.

The results of the weighted averaging modeling showed mixed results. The modeling under predicted the present day phosphorus concentrations in Norrie Lake (10 vs 30 µg L^{-1}). This is likely because the pH of the lake is low which affects the diatom community. All of the low pH lakes in the calibration dataset have low phosphorus concentrations so the model results are erroneous. The diatom community suggests that phosphorus, concentrations and probably water color, in this lake have increased during the last century. This is indicated by the shift from *A. perglabra* var. *floriniae* at the bottom of the core to *A. ralfsii* var. *americana* at the top of the core. The latter diatom is found in humic-stained waters with high nutrient concentrations (Camburn and Charles 2000, Siver et al. 2005).

The model appears to not predict phosphorus concentrations well for Big Bass and Mission lakes. However, samples collected apart from this study measured concentrations very similar to the modeling results. These lakes may experience fluctuations in summer phosphorus levels from year to year so the model results may not always reflect measured phosphorus concentrations. The model results likely can be used to determine trends in the phosphorus levels. Another factor affecting the modeling is the presence of high water color in all the lakes except for Big Bass and Wadley lakes. Garrison et al. (2008) found that color and phosphorus covaried in shallow lakes. The diatom community changes suggest that at the present time water color is higher than it was historically. It is likely the change in color is adversely affecting the modeling for phosphorus.

Because Big Bass and Wadley lakes have low color, the inferred summer phosphorus modeling should be most accurate for these lakes. Both lakes appear to have higher phosphorus concentrations at the present time compared to pre-settlement times (Table 4). Phosphorus levels in Big Bass at the present time are nearly twice as high. Levels in

Table 4. Diatom inferred summer mean phosphorus concentrations.

Lake		Summer Phosphorus ($\mu g\ L^{-1}$)
Big Bass	Top	19
	Bottom	10
Mayflower	Top	25
	Bottom	29
Mission	Top	33
	Bottom	29
Norrie	Top	10
	Bottom	9
Pike	Top	30
	Middle	29
Wadley	Top	15
	Bottom	11

Wadley have increased nearly 50%. Phosphorus levels in Mission Lake have increased smaller amounts while levels in Pike and Mayflower have changed little. Again, these model results may not be entirely accurate because of the change in water color that happened at the same time.

Along with the increase in water color and phosphorus in most of these lakes, there have been significant changes in the habitat of many of these lakes. Most of the lakes have more submerged aquatic plants and a greater expanse of filamentous soft bodied algae. Numerous other paleolimnological studies on lakes in northern WI have shown that lakes with shoreland development have experienced little change in phosphorus but significant changes in habitat. Borman (2007) found that in northwestern Wisconsin the macrophyte community often changed in seepage lakes, from one dominated by low growing plants to a community dominated by larger macrophytes, as a result of shoreline development. The structure of the macrophyte community changes because the increased runoff of sediment during construction on the shoreline enables the establishment of the larger plants. With the larger plants there is much more surface area available on which diatoms and other periphytic algae are able to grow. This appears to have occurred in many of the lakes in this study. With the increase in aquatic plants there is more surface area for attached algae to grow. While macrophytes obtain most of their phosphorus from sediments the attached algae obtain most of their nutrients from the water column. Consequently there is little increase in measured phosphorus levels because it is incorporated into the algae.

Summary

At the present time all of the lakes except Big Bass and Wadley have humic-stained waters. The diatom community indicates, historically this was not the case. It is likely these lakes had some water color but it is higher now. This has

resulted in a loss of water clarity. It is likely there has also been an increase in phosphorus at the present time. The reason for this may be that with agricultural development there is more surface runoff which flushes the surrounding wetlands faster thus resulting in more stained water entering the lakes. The best example of this is Norrie Lake. Historically this lake had low phosphorus concentrations and low to moderate water color. The dominant diatom in the surface sample is *A. ralfsii* var. *americana* which has been found in the northeastern USA in lakes with humic stained water and high nutrient concentrations.

The two clear water lakes, Big Bass and Wadley, historically had low phosphorus concentrations with submerged aquatic vegetation. At the present time phosphorus levels are higher there are more abundant macrophytes and soft bodied filamentous algae.

Mission and Mayflower lakes appear to have experienced a significant change in habitat with shoreland development. Many other lakes in central and northern Wisconsin have seen similar impacts from shoreland development. Although this study is not designed to document degradation of habitat on shore that other studies have found is common, this study does show that with development there often is increased growth of macrophytes and filamentous algae. The periphyton attached to these communities acts as a buffer to inputs of nutrients from shoreland runoff by incorporating nutrients into their plant tissues. Other studies in Wisconsin have shown that if nutrient runoff increases sufficiently, this buffer is overwhelmed and increased phosphorus levels occur in the open water of the lake (Garrison and Wakeman 2000). Some of these Marathon County lakes are typical of many Wisconsin seepage lakes with shoreland development in that they have experienced limited increased concentrations of phosphorus but large changes in habitat during the last century.

Acknowledgments

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